

# Radiation Shielding for Space Flight

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## Abstract

A safe and efficient exploration of space requires an understanding of space radiations so that human life and sensitive equipment can be protected. On the way to these sensitive sites, the radiation is modified in both quality and quantity. Many of these modifications are thought to be due to the production of pions and muons in the interactions between the radiation and intervening matter. A method to predict the effects of the presence of these particles on the transport of radiation through materials is presented.

## 1 Introduction

In space, the radiation environment is more intense than on the earth's surface. For any activity in space, the effects of this radiation on

- biological systems (astronauts)
- electronic systems

must be determined, and damage to these systems must be prevented. Our goal here is to develop analytical and computational techniques that will allow efficient and reliable missions analysis.

This task requires knowledge of the radiation fields at these sensitive sites. Both

- the initial space radiation environment
- modifications due to intervening materials (spacecraft walls etc.)

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need to be determined.

In order to calculate how the radiation is modified, two major things are needed

- a data-base describing the major interactions between the radiation and materials
- a radiation transport formalism that uses this data-base to determine how the radiation fields change as they move through materials.

In particular, we are interested in determining how the production of pions and muons effects the radiation dosages received in space flight.

## 2 Radiation Transport Formalism

A set of coupled linear integro-differential equations called the Boltzmann transport equation describes how radiation changes as it moves through materials. The set consists of one equation for each of the different types of particles that make up the radiation. These types include neutrons and ions ranging from hydrogen up to iron as well as more exotic particles like pions and muons. These equations are impossible to solve in general so an approximate solution method of Wilson *et al.* [1] was used.

In general, the particle fluxes are a function of six variables, 3 spatial and 3 momentum. The characteristics of the radiation in space make approximations possible that reduce these variables to just 2 variables: 1 spatial dimension and energy. The simplified 1-D solution can be solved perturbatively for small distances  $h$ . This perturbative solution can then be iterated to achieve transport over arbitrary distances as shown in Wilson *et al.* [1] and Blattnig *et al.* [2].

$$\phi(x + h) \approx \phi(x) \times \dots \quad (1)$$

The full 3-D solution can then be obtained by a superposition of the 1-D solutions due to the linearity of the transport equations. The flux at a point in an object can be calculated by transporting the fluxes from the surface to the point along several rays and then adding up the results with the appropriate weightings. Once the fluxes are known, other quantities of interest, such as dose, can be calculated.

## 3 Pions and Muons

Pions are unstable particles that are abundantly produced in high energy nuclear collisions. They have a charge of either  $e$ ,  $-e$ , or  $0$  where  $-e$  is the charge of an electron. Neutral pions do not have to be transported because they decay almost immediately. Charged pions decay into like charged muons and a neutrino. Muons can have a charge of  $\pm e$  and a mass of approximately two hundred times that of an electron. They decay into an electron or

positron, depending on the charge, and two neutrinos. Muons are otherwise identical to electrons.

Pions and muons are not present in significant amount in the initial cosmic ray spectrum. They are produced in the interaction of cosmic rays with materials. Pions will therefore become an important consideration for radiation protection when there are many of these interactions. The more material traversed by the radiation, the more important pions become. Muons are produced mainly from pion decay and will be important when there are many pions produced that have enough time to decay. This will mainly occur with thick low density materials.

We have been working to extend the existing NASA transport code HZETRN [3] to include pions and muons in the transport calculations [2]. Pions are produced in abundance by interactions of high energy Galactic Cosmic Rays (GCR) with materials.

Including pions and muons in transport calculations requires:

- appropriate perturbative solution to the transport equation.
- nuclear mean-free paths
- rates of pion and muon production
- energy loss due to electromagnetic interactions

The perturbative solution for pion and muon transport was calculated in a manner similar to that given in Wilson *et al.* [1], but slightly different approximations were used. A combination of parameterizations and theoretical calculations were used for the rest of the quantities. Details can be found in Blattnig *et al.* [2, 4].

## 4 Results and Conclusions

Using the solution to the transport equation and the database that was outlined above, charged pion and muon fluxes were calculated at various depths of aluminum and water. These materials were chosen because aluminum is commonly used in the construction of spacecraft, and water is a very large component of human tissue. The initial fluxes were given by the model for the 1977 solar minimum described in Wilson *et al.* [1]. The results of this calculation are given by the figures.

Figure (1) shows the sum of the charged pion and muon fluxes at various depths in the aluminum and water. These fluxes steadily increase as more matter is traversed. Figure (2) is the same as figure (1) except the percentage of the total radiation flux is shown.

The pion fluxes make up a large percentage of the flux at large values of kinetic energy. There are two things to note here concerning the large percentages.

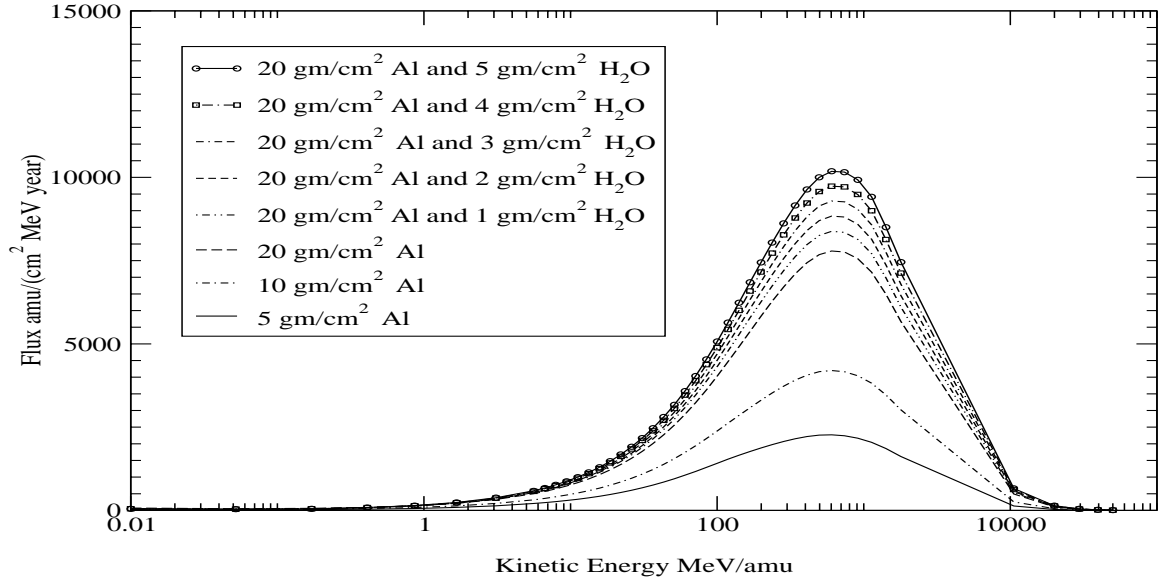


Figure 1: Pion and muon fluxes after transport through increasing depths of aluminum and water, for the 1977 solar minimum as functions of kinetic energy.

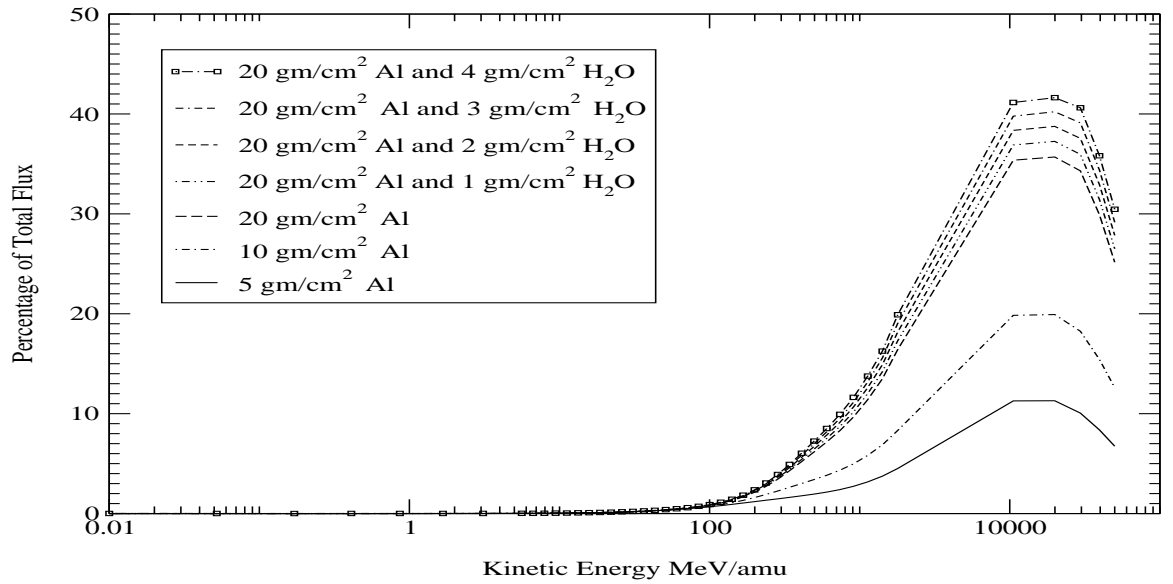


Figure 2: Percentage of the total flux due to the sum of pion and muon fluxes, after transport through various depths of aluminum and of water for the 1977 solar minimum.

- The percentage is large at high energy where the rest of the fluxes are small, even the pion fluxes are relatively small here. This implies that the percentage of the integrated (over energy) flux made up by the pions will still be small.
- The kinetic energy is actually a kinetic energy atomic mass unit, so pions are being compared to protons with 6 or 7 times as high actual kinetic energy. Since the initial cosmic ray flux falls off rather sharply with energy, the percentage for pions is greatly increased when plotted in these units.

Muon fluxes are negligible compared to the pion fluxes. The muon fluxes are low simply because there is not enough time for a significant amount of pions to decay. Muons might be much more important for less dense shielding such as the martian atmosphere.

In summary, a one-dimensional deterministic muon and pion transport code was developed. This code is capable of transporting pions and muons over arbitrary distances for a wide variety of materials when it's coupled to the ion and neutron transport code HZETRN. All the needed cross sections were either derived or taken from other sources. Example results for transport through aluminum and water were presented and shown to be reasonable. The major shortcomings of this calculation are as follows:

- Numerical convergence is slow for low energy pions and for transport through low density materials.
- The parameterizations of cross sections describing pion production were based mainly on high energy data. The physical mechanisms for pion production are different at low energy, so the cross sections based on high energy data will be somewhat inaccurate at low energy.

Both of these shortcomings are presently being addressed.

## References

- [1] J. W. Wilson *et al.*, NASA RP 1257, (1991).
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- [4] S. R. Blattnig *et al.*, Phys. Rev. D62, 94030 (2000); Also S. R. Blattnig *et al.*, NASA TP 210640 (2000).